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NONDESTRUCTIVE TESTING USING TRW /ACUSTO-OPTICAL IMAGING SYSTEM

January 1972

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INTERIM REPORT - CONTRACT DAAG46-70-C-0103

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ABSTRACT

The technique of Acousto-Optical Imaging (AOI) enables one to "see", on a real-time basis, within optically opaque materials and to detect internal or surface flaws and/or other irregularities which might be present. The process uses an ultrasonic beam to probe the object under study. As it interacts with the object, the ultrasonic beam acquires an acoustical "picture" of the object. The acoustic waves then interact with a monochromatic light beam (as from a laser). Optical sidebands are produced by the Bragg diffraction of light. The cumulative result of this process is that these sidebands produce a visual image of the interior of the object. This report discusses the results of an analytical and experimental study to evaluate the applicability of acousto-optical imaging to nondestructive testing. In addition to the determination of the system resolution, the effects of specimen thickness, geometry, composition and surface roughness were investigated. A new technique which utilizes the sound reflected from the specimen to obtain an acousto-optical image was also developed. Results using this technique to detect known internal flaws on a specimen are in good agreement with the actual flaws.

FOREWORD

The work reported was performed by the Advanced Technology Staff Group of Space Vehicles Division, TRW Systems, Redondo Beach, California. It was sponsored by the Advanced Research Projects Agency (ARPA Order No. 1245). It was performed under Army Materials and Mechanics Research Center Contract No. DAAG46-70-C-0103 with Mr. O. R. Gericke, Chief, Nondestructive Testing Branch, AMRC, as technical monitor. Project Manager at TRW Systems was Mr. R. Aprahamian with technical support provided by Mr. J. L. Jacoby, Dr. P. G. Bhuta and Mr. C. V. Murrow. The authors wish to thank Mr. O. R. Gericke for his very valuable help and suggestions throughout the course of this investigation.

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INTRODUCTION AND SUMMARY

The technique of Acousto-Optical Imaging (AOI) enables one to "see" on a real-time basis, within optically opaque materials and to detect internal or surface flaws and/or other irregularities which might be present. The process uses an ultrasonic beam to probe the object under study. As it interacts with the object, the ultrasonic beam acquires an acoustical "picture" of the object. The acoustic waves then interact with a monochromatic light beam (as from a laser). Optical sidebands are produced by the Bragg diffraction of light. The cumulative result of this process is that these sidebands produce a visual image of the interior of the object. A more detailed discussion of this technique can be found in Reference 1.

Previous nondestructive testing work with the acousto-optical imaging system has used transmitted sound waves to probe the material being inspected, i.e., the acoustic waves were passed through the specimen. Testing situations often arise, however, in which access to both sides of the specimen is not possible. In these cases, it is necessary to be able to inspect the parts from one side. This can be accomplished by placing the acoustic transducer and the light-sound interaction zone on the same side of the specimen and producing an image using the sound which has been reflected from the flaw. Furthermore, previous tests have shown that it is advantageous to use pulsed light and sound sources in such a system. It is the objective of this study to further exploit the pulse-echo technique for acousto-optical imaging and to determine its applicability to nondestructive testing.

A working model of a pulse-echo acousto-optical imaging system was designed and fabricated and is operating in the laboratory. The system has the ability to investigate materials which have not been submerged. A flexible diaphragm contains the water of the Bragg cell and couples the sound to the specimen. The ability of this system to detect internal flaws in metallic specimens is currently under investigation.

To date, images have been obtained of several specimens containing holes drilled part way into them from the rear side. Images were obtained

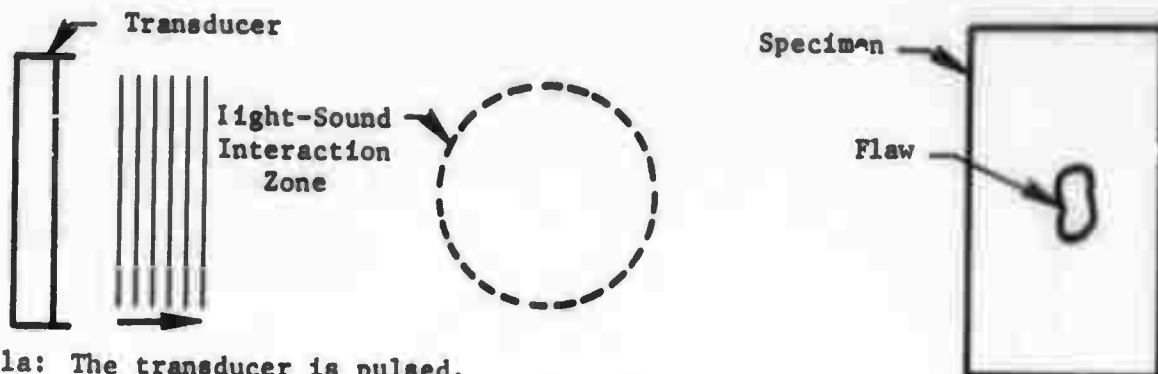


Figure 1a: The transducer is pulsed.

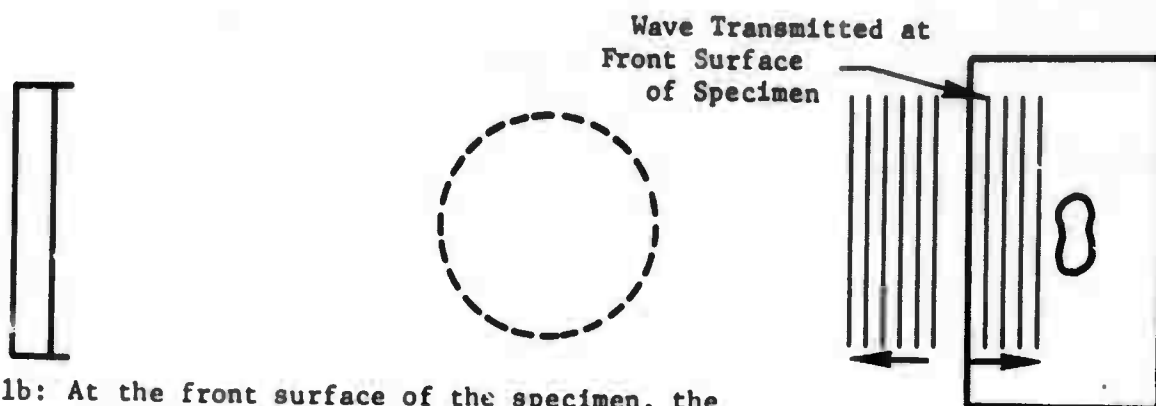


Figure 1b: At the front surface of the specimen, the wave splits into reflected and transmitted parts.

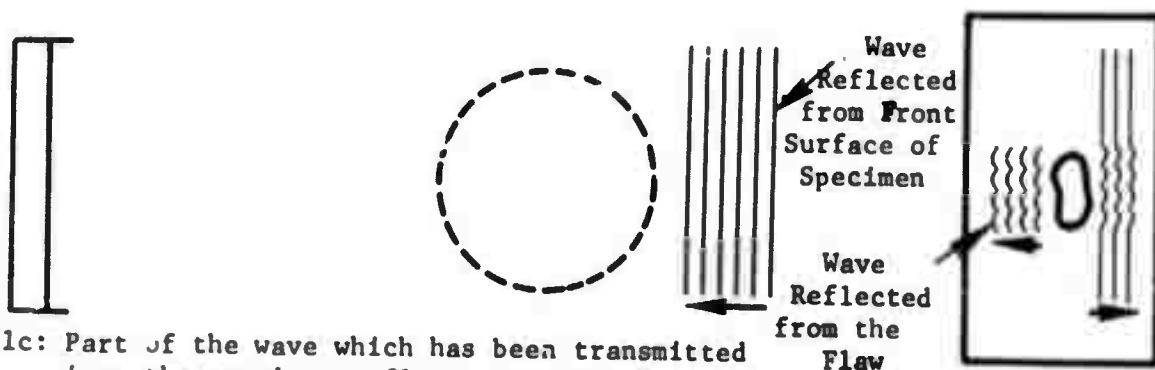


Figure 1c: Part of the wave which has been transmitted into the specimen reflects from the flaw.

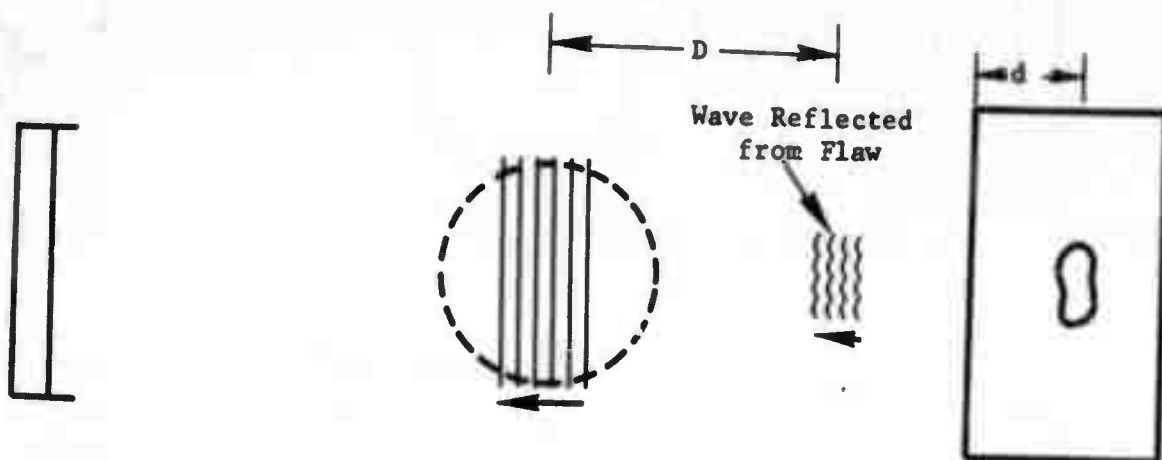


Figure 1d: The wave reflected from the flaw leaves the specimen.

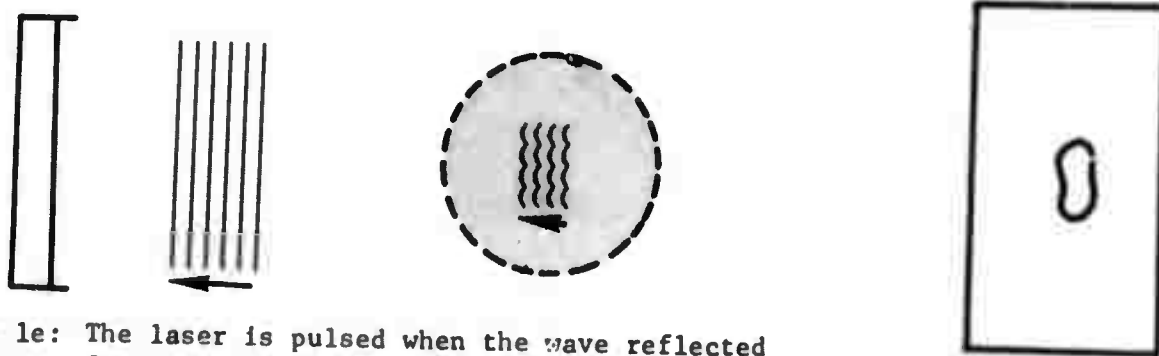


Figure 1e: The laser is pulsed when the wave reflected from the flaw enters the light-sound interaction zone.

of the bottoms of the holes. This is analogous to detecting voids in the specimens. Range-gating was demonstrated as a technique for measuring the depth of the flaw in the material.

DESIGN STUDY FOR PULSE-ECHO ACOUSTO-OPTICAL IMAGING

Figure 1 shows schematically how pulsed light and sound sources can be used in synchronization to image a flaw which is internal to an object. This pulse operation allows the acoustic reflection from the front surface of the specimen to be rejected. This is accomplished by pulsing the laser only when the acoustic wave, which has interacted with the flaw, is in the light-sound interaction zone. The quality of the image obtained and the accuracy with which its position is known is determined by a number of design parameters such as pulse widths, pulse repetition rates, acoustic frequency and geometry of the Bragg cell and specimen. An analysis was performed to determine an initial system design which would be compatible with the objectives of this study and with the available hardware.

The pulse technique will enable the use of range gating to determine the depth of the flaw in the specimen. This can be accomplished if a short acoustic spatial pulse length, ΔL , is employed.

$$\Delta L = v_s \Delta t \quad (1)$$

v_s = velocity of sound in the specimen

Δt = duration of pulse.

Referring to Figure 1d, it is desirable that ΔL be less than twice the flaw depth ($\Delta L < 2d$) so that sound reflected from the flaw will not interfere with sound reflected from the front surface of the specimen.

The spatial separation between these two reflections is given by $D = 2d \frac{v_s}{v_o}$, where v_o is the sound velocity in the medium surrounding the specimen. This requirement is somewhat flexible because even in the

situation when the images of the front surface and internal flaws are superimposed, it is still possible to identify the internal flaws. A short acoustic pulse width is also desired so that the error in the measurement of the flaw depth will be minimized. A pulse width of 1 μ sec is compatible with the acoustic frequencies which will be used (12-20 MHz). From Equation 1, this would yield a spatial pulse length in an aluminum specimen of about 1/2 cm.

The pulse repetition rate must be sufficiently high to permit continuous viewing and yet low enough so that two pulses will not interfere with each other. The amplitudes of the light and sound pulses are approximately independent of the repetition rate so that a higher average power will be achieved with a higher rate. Pulse rates greater than 30 Hz are sufficient to allow for continuous viewing without any annoying flicker of the image. Pulse separations on the order of one millisecond would be sufficient to insure that no interference would occur between two separate pulses. The pulsed power oscillator to be used for these tests has a variable repetition rate of 50 Hz to 1200 Hz and can also be synchronized with the power line frequency of 60 Hz. The laser is capable of repetition rates up to 100 Hz. The television camera and monitor used to display the image scan at a rate of 60 Hz, locked to the power line frequency. Thus, it would appear that a pulse repetition rate of 60 Hz meets all of the design requirements and is compatible with all of the equipment.

The design requirements for the light source are that it provide pulses of monochromatic light in the visible regime. The pulse lengths should be on the same order as the acoustic pulse lengths ($\sim 1 \mu$ sec). There are a number of types of gas lasers which can easily meet the requirements for this system.

FABRICATION OF PULSE-ECHO ACOUSTO-OPTICAL IMAGING SYSTEM

In 1971, TRW constructed, using company capital funds, a pulsed xenon laser for use in pulse-echo acousto-optical imaging. This laser produces pulses of 1 microsecond duration at energies greater than

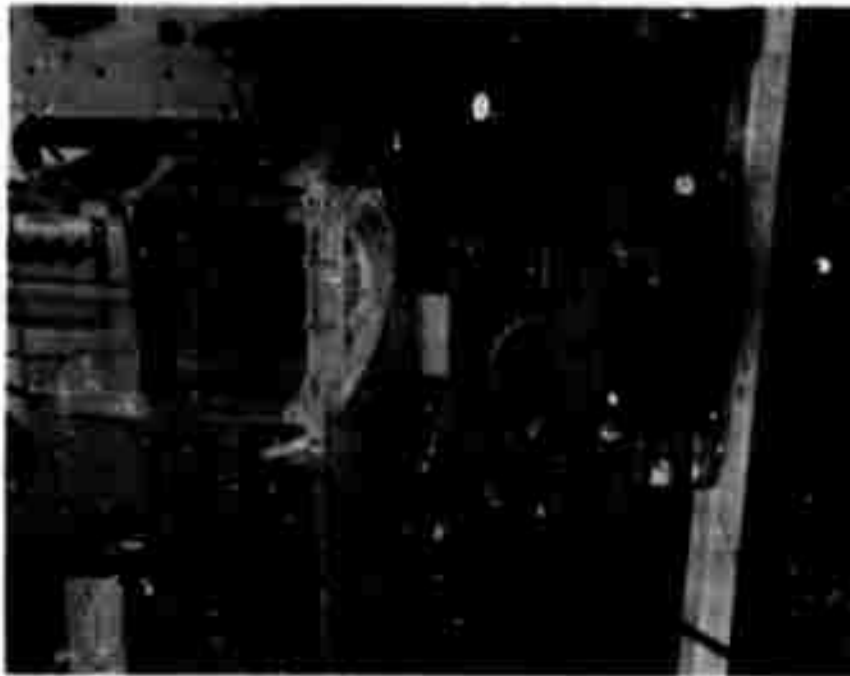
1000 watts (peak). Since the output of this laser consists of five principal wavelengths, an interference filter is used to select the strongest one. In this case, the output is green having a wavelength of 5353Å. It was found that when this laser was operated at a higher power and at a high repetition rate for an extended length of time, overheating resulted. Therefore, modifications were made to provide for additional cooling of the laser. These included placing the laser tube into an oil bath which in turn could be cooled by water coils.

The ultrasonic pulsed power oscillator, which is being used to drive the transducer, is capable of producing pulses of from 4 to 25 μ sec duration. As short acoustic pulses are desirable, minor modifications in the oscillator output stages are planned which will shorten the minimum pulse width to 1 μ sec. This oscillator also provides trigger signals with variable delays so that the laser pulse can be timed properly with respect to the acoustic pulse.

A Bragg cell was fabricated which allows for the inspection of a specimen without submersing it in water. The design allows the Bragg cell to be placed on top of the test specimen. An acoustically transparent diaphragm contains the water in the Bragg cell, yet provides an acoustical coupling between the water and the test specimen. At present, a thin sheet of mylar is being used for the diaphragm; however, the use of other materials, such as pc-rubber, is being investigated. Photographs of the Bragg cell, showing the relative positions of the acoustic transducer and the light cone, are shown in Figure 2 with (a) a test specimen lowered, and (b) a test specimen in contact with the mylar diaphragm. While the present configuration requires the specimen to be raised up to the diaphragm, it is anticipated that a prototype system would be sufficiently portable to allow it to be placed on or next to the specimen. Figure 3 shows the laboratory test set-up of the pulse-echo acousto-optical imaging system.

EXPERIMENTAL PROGRESS WITH LABORATORY SYSTEM

The positioning and alignment of the various system components is more critical for this reflection system than for the transmission system



(a) Test specimen lowered



(b) Test specimen in contact with
mylar diaphragm

Figure 2: Bragg cell showing relative orientation of acoustic transducer, light cone and test specimen.

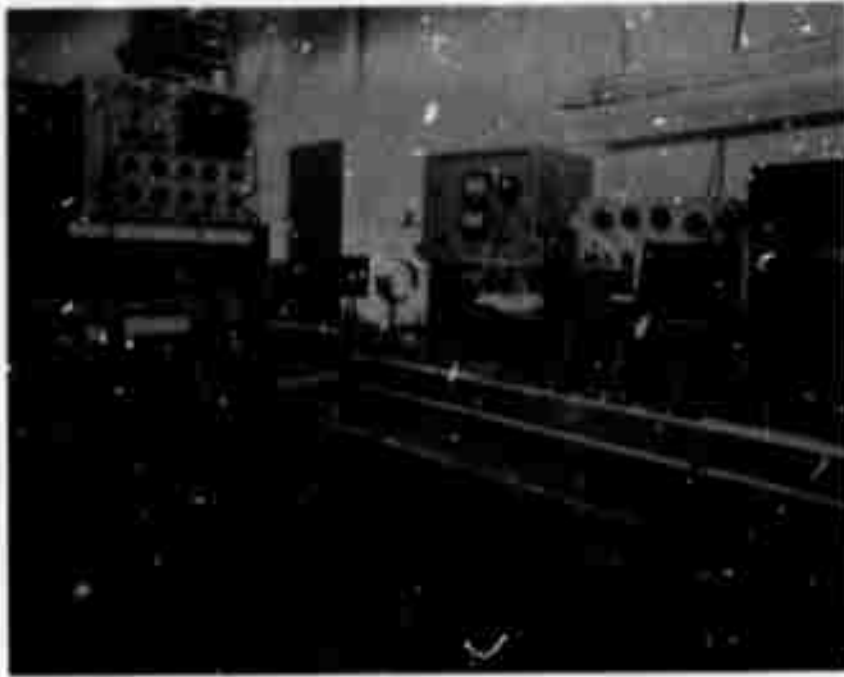
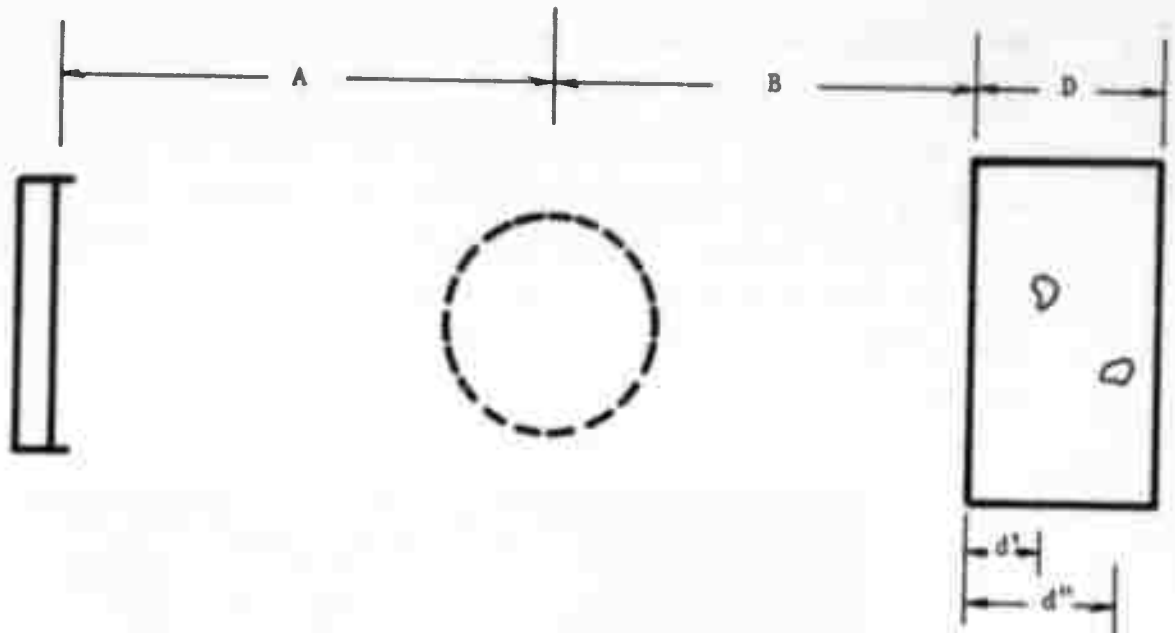


Figure 3: Laboratory test set-up of the pulse-echo acousto-optical imaging system.

which was used earlier. The specimen must be carefully aligned to the transducer and to the light cone (the light-sound interaction region) so that the reflected acoustic pulses are imaged. The timing of the laser pulse must be very accurate in order to image the correct reflection. Figure 4 illustrates how long the laser must be delayed in order to image various parts of the specimen. To get an idea of the actual numbers involved, the velocity of sound in water, v_o , is ~ 1.5 cm/ μ sec and the velocity of sound in an aluminum specimen, v_s , is ~ 0.6 cm/ μ sec. Adjustments in the laser timing must be accurate to better than 1 μ sec.

An interesting problem occurred during the initial experiments with this system which is worth noting here. An image was obtained which was thought to have been reflected from the rear surface of the specimen, and the timing of this signal agreed with the specimen thickness. However,



Part of Specimen to be Imaged

Laser Delay

Front Surface

$$(A + 2B)/v_o$$

1st Flaw

$$(A + 2B)/v_o + 2d'/v_s$$

2nd Flaw

$$(A + 2B)/v_o + 2d''/v_s$$

Rear Surface

$$(A + 2B)/v_o + 2D/v_s$$

v_o = velocity of sound in water medium

v_s = velocity of sound in test specimen

Figure 4: Timing of the laser in order to image various parts of the test specimen.

when specimens having different thicknesses were substituted, the "rear surface" reflections arrived at the same time. It was determined that the reflection from the front surface of the specimen was returning to the transducer and then being reflected into the light-sound interaction region. (Note that the transducer had been aligned parallel to the specimen surface.) Referring to Figure 4, this occurred because the situation arose where $(3A + 2B)/v_o = (A + 2B)/v_o + 2D/v_s$ or, $A/v_o = D/v_s$.

The transducer was moved away from the light-sound interaction region (i.e., A was increased) so that this coincidence would no longer occur.

Having solved the above problem, no difficulty was encountered in obtaining an image from the rear surface of a specimen. The next step was to use an aluminum specimen which had four holes drilled approximately half way into it from the rear side. The diameters of these holes were $7/16"$, $3/8"$, $1/4"$ and $1/8"$. This specimen is shown in Figure 5. A pulse-echo acousto-optical image was obtained of the four holes in this

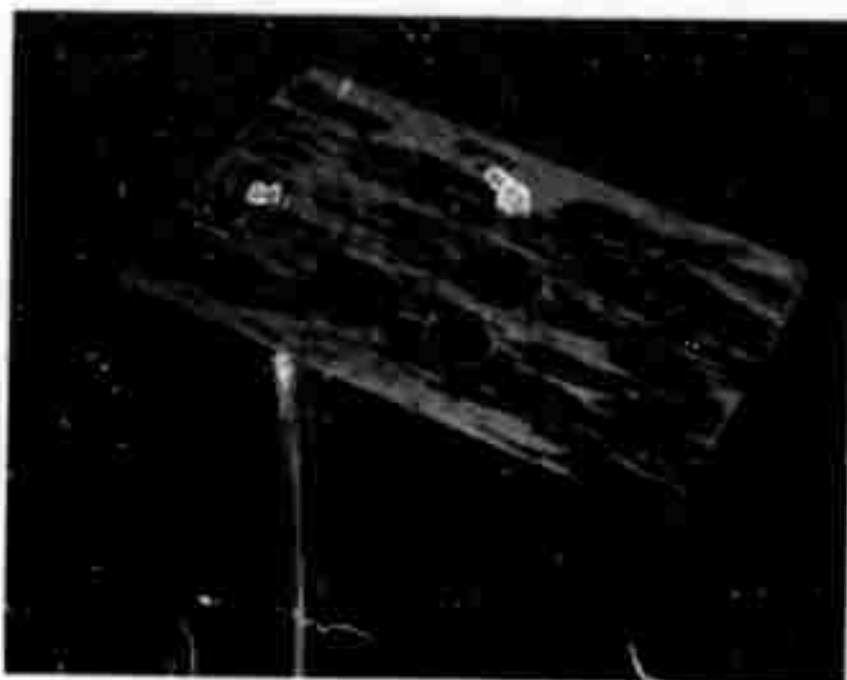


Figure 5: Test specimen containing four holes drilled half way into the specimen. The hole diameters are $7/16"$, $3/8"$, $1/4"$ and $1/8"$. Note that the side shown here faces away from the imaging system.

specimen (Figure 6). It is possible that the nonsymmetry in the image is due to the sound reflecting from the specimen at other than normal incidence.

Another specimen was fabricated to determine the systems ability to measure the depth of a flaw by range-gating the acoustic signal. This



Figure 6: Pulse-echo acousto-optical image obtained of specimen shown in Figure 5.

aluminum specimen had two holes drilled into it from the rear. The depths of the holes drilled into it from the rear. The depths of the holes differed by 1/2 inch. This specimen is shown schematically in Figure 7. Either of the two holes could be imaged by using the proper delay for the laser. Due to the long acoustic pulse used, both holes could be

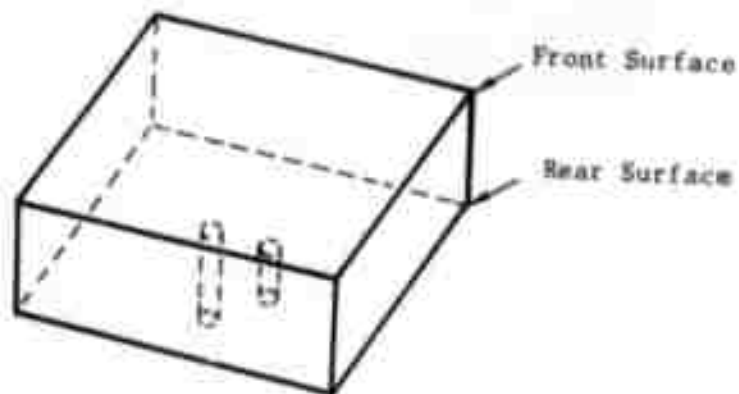


Figure 7: Schematic of aluminum test specimen with two holes drilled to different depths.

imaged simultaneously by setting the laser delay at a point midway of the other two settings. The various images obtained with this specimen along with the corresponding relative laser delay times are shown in

Figure 8. Table I compares the flaw depths computed from these tests with the measured flaw depths.

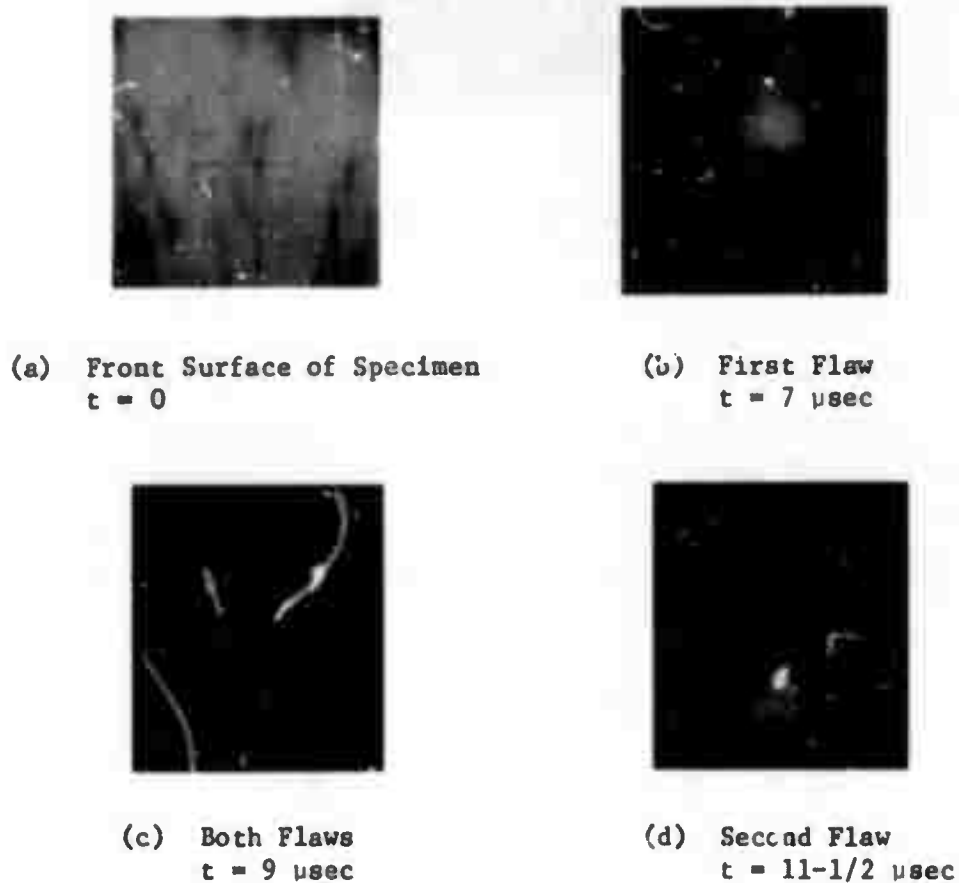


Figure 8: Range-gating determination of flaw depth in aluminum specimen.

TABLE I

Depths of Flaws in Aluminum Test Specimen

	<u>Time Delay</u>	<u>Depth determined from Range-Gating</u>	<u>Measured Depth</u>
First Flaw	7 μsec	2.1 cm	1.7 cm
Second Flaw	11-1/2 μsec	3.4 cm	3.0 cm
Difference in Flaw Depths	4-1/2 μsec	1.4 cm	1.3 cm

The data presented in Table I suggests that the timing of the front surface reflection, $t \approx 0$, is in error as both flaw depth measurements were calculated too high. The relatively long acoustic pulse used, $\sim 4 \mu\text{sec}$, also contributed to the error.

CONCLUSIONS

The feasibility of using the pulse-echo technique of acousto-optical imaging to detect internal flaws in metallic specimens has been shown. In addition, the use of a mylar diaphragm to contain the water of the Bragg cell and thus permit inspection of an object which has not been submerged was demonstrated. During the next phase of this study, quantitative measurements will determine the sizes of flaws which can be detected as well as the accuracy with which the flaw position can be measured. Larger acoustic transducers will be used to increase the specimen area which can be covered.

REFERENCES

1. R. Aprahamian, J. L. Jacoby, and P. G. Bhuta, "Nondestructive Testing using TRW Acousto-Optical Imaging System", Semi-Annual Report, Contract DAAG46-70-C-0103, prepared for Army Materials and Mechanics Research Center, August 1971.

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